NBS

Technical Note 188

CALIBRATION OF VOLT-AMPERE CONVERTERS

E. S. WILLIAMS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

THE NATIONAL BUREAU OF STANDARDS

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NATIONAL BUREAU OF STANDARDS

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Calibration of Volt-Ampere Converters

E. S. Williams

These notes have been prepared to describe the National Bureau of Standards calibration services for volt-ampere converters (or transfer volt-ammeters), to suggest procedures for d-c standardization in the user's laboratory, and to describe a voltage comparator which can be used to make such calibrations quickly and easily.

1. General

A volt-ampere converter, shown schematically in figure 1, incorporates a thermoelement connected in series with a resistive multiplier for alternating voltage measurements or in parallel with a shunt for alternating current measurements. (Multi-range switching is not shown in the figure.) With alternating current applied to the heater of the thermoelement, the output emf of the thermocouple is balanced against an adjustable internal d-c source as indicated by a null on a galvanometer. (This is usually called the No. 1 or A-C balance). The heater is then switched to a second internal d-c source which is adjusted to give the same thermocouple emf. (This is the No. 2 or D-C balance). The direct voltage, V_t, is then measured with a suitable potentiometer. The alternating input voltage or current is equal to the output voltage (V_t) multiplied by a simple factor, usually shown directly on the dial of the range switch. The basic equations [1 and 2][1] are shown in figure 1. More complete diagrams and additional information are given in the references.

A modification of this arrangement uses a decade multiplier or decade

[1]Figures in brackets indicate the literature references on page 14.

shunt, with a two-coil milliammeter as an error indicator, as shown in simplified form for voltage measurements in figure 2.[2] The torques of the two milliammeter coils are in opposition, and the second coil is energized by a zener diode reference-voltage source. When balances of the galvanometer are obtained in the A and then the B positions, by adjusting d-c supplies 1 and 2 respectively, the error indicator shows directly the percent difference between the input voltage or current and the quantity indicated by the setting of the decade multiplier or shunt dials of the converter.

Volt-ampere converters are normally standardized at NBS only to determine their ac-dc differences. These differences depend on the reactances of the measuring circuit and normally increase with frequency. Determinations are therefore usually made only at the highest rated frequency. Because the differences are small and relatively permanent in a well-designed and well-constructed instrument, they ordinarily need to be redetermined only if the instrument is altered or damaged. However, for additional assurance, it is recommended that the ac-dc tests be repeated at intervals of not less than five years, if the converter is to be used in the upper part of its frequency range. The ac-dc differences are not affected appreciably by ordinary changes in laboratory temperature or changes in applied voltage or current on a given range.

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[2] An instrument of this type has been built by the Sensitive Research Instrument Corporation, 310 Main Street, New Rochelle, New York, and is described in their house organ, "Electrical Measurements," <u>28</u>, No. 5, May 1961.

For these reasons, only periodic d-c calibrations should be necessary to verify the continued accuracy of a volt-ampere converter in service. These periodic d-c calibrations can, in most cases, be made in the user's own laboratory. This is an important advantage of this type of instrument, because the accuracy of a-c measurements can be maintained with relatively simple d-c calibration techniques. A calibrated potentiometer is a necessary accessory to the instrument and must be at hand; the only additional calibrated equipment needed is a shunt box and a volt box. Normally these would be readily available in an instrument-testing laboratory. Alternatively, the voltage comparator described in these notes will save time and effort.

It is recommended that d-c tests be made at rated voltage or current on each range and at 50 percent of rated value on the highest and lowest ranges, at intervals of 6 to 12 months for normal service. The d-c correction thus determined is practically independent of voltage or current level on a given range if the design of the converter includes compensation (R_m' and R_s') for the resistance of the heater of the thermoelement which does depend on the applied current.

2. Potentiometer Method for Volt-Ampere Converter Calibration

For d-c tests of the converter voltage ranges, a potentiometer and volt box are used to measure the voltage across the input terminals of the converter. Then, after the proper balances of the converter are made, the potentiometer is used to measure the output voltage of the converter, as shown in figure 3. The correction to the range factor of the converter is calculated from these two potentiometer readings and the

known ratio of the volt box. For tests of the current ranges a shunt is used as shown in figure 4.

2.1 Calibration Circuits

Volt-ampere converters generally have a small reversed d-c difference, so that the average for the two directions of the current must be used as a d-c reference. The circuits of figures 3 and 4 show a convenient switching arrangement which provides for reversing the test current and the leads to the potentiometer. It is more convenient if S_{1a} and S_{1b} are ganged together.

Short, low-resistance leads (less than 0.01 percent of the input resistance of the converter) should be used between the volt box and the volt-ampere converter. The common or ground terminal of the instrument and the low-voltage end of the volt box should be grounded as shown in the figure.

It is advantageous (although not necessary) to select shunts and volt-box ranges of such value that their nominal output voltage is the same as that of the converter. Such an arrangement will help to save time by allowing the two measurements to be made without resetting the main potentiometer dials. It will also tend to minimize the effect of potentiometer errors, since it is only the difference between the two readings that is significant.

It is very important that the metal case of a potentiometer which is internally connected to the emf circuit should not be directly grounded, since this would comprise a second ground. If an auxiliary emf dial is provided, it may be connected to the V_s circuit, following the directions

given by the manufacturer. This makes it unnecessary to reset the dials when switching to V_t. Note that a potentiometer reversing switch may still be required in this circuit.

If the volt-ampere converter has a built-in potentiometer, this potentiometer should first be calibrated. This can often be done conveniently by comparison with a general purpose potentiometer having known corrections. For the calibration of the converter, the built-in potentiometer is then used to measure the output of the volt-ampere converter, and the general purpose potentiometer is connected to the shunt or volt box. Alternatively the internal potentiometer can be used with a suitable switch to measure first the voltage of the standard shunt or volt box and then the volt-ampere converter, as already outlined.

Stable d-c supplies of voltage and current are necessary, and the observer at the potentiometer must have the fine supply controls within his reach. Two observers are required for the test.

2.2 Precautions

Because the frequency response of thermoelements such as those used in volt-ampere converters extends to many megacycles, interference from TV stations and other sources of rf fields can sometimes be troublesome unless a filter is incorporated in the leads to the heater of the converter or, in extreme cases, the instrument is used in a shielded room. A quick check of this interference is easily made, however. With the input terminals of the converter connected to the calibrating circuit but with the source disconnected, and with a potentiometer connected to the "potr" terminals, (V_t in figure 1), adjust the No. 1 control on the instrument

(with the transfer switch in No. 1 (A-C) position) for minimum deflection of the converter galvanometer. There should be no noticeable change in the deflection when the input terminals are short-circuited. Similarly, after a balance has been obtained (at any settings of the No. 1 and No. 2 controls) with the transfer (selector) switch in the No. 2 (D-C) position, there should be no change in galvanometer deflection when a capacitor (at least 2000 pf) is connected across the "potr" terminals (V_t in figure 1). Such a capacitor will effectively short-circuit any rf current picked up in the potentiometer circuit.

Many bead-type thermoelements (having an electrically-insulating bead between the heater and thermocouple) exhibit a small exponentially-decreasing drift of emf for the first few minutes after a steady heater current is applied. This does not ordinarily cause a significant error, but, for the most accurate results, a wait of a minute after each large change in heater current is desirable.

The sensitivity and stability should be checked after warm-up but before the formal test is begun. For a check of sensitivity, select any convenient range, turn S_2 (figure 3 or 4) to the V_s position, and the transfer (selector) switch on the converter to the No. 1 (A-C) position. With the potentiometer set to the corresponding nominal value, adjust the input voltage or current until the potentiometer is balanced. Then balance the converter in the No. 1 position. Change the potentiometer dials by 0.1 percent, readjust the input to rebalance the potentiometer and note the change in deflection of the galvanometer in the converter. An abnormally low sensitivity is usually an indication that the

thermoelement is faulty. Then, to check stability, keep the voltage constant and observe the galvanometer deflection for a few minutes. The drift should be less than 0.01 percent per minute. The error introduced from this source is mainly dependent upon the time needed by the operator between setting the No. 1 controls of the converter and balancing the potentiometer after setting the No. 2 controls. An excessive drift is usually remedied by replacing the internal batteries.

2.3 Procedure

After preliminary settings of the input controls and adjustment of the No. 1 and No. 2 controls of the converter, an observer at the potentiometer adjusts the voltage or current to balance the potentiometer at the desired setting, with switch S_2 in the V_s position (figure 3 or 4). The second observer adjusts the No. 1 (A-C) balance controls on the converter until the galvanometer is set exactly on a scale mark near the null position. The transfer switch on the converter is then turned to the No. 2 (D-C) position, and the No. 2 balance controls are adjusted for the same galvanometer position as was set in the first balance. The potentiometer observer meanwhile switches to the V_t position and, while the No. 2 setting is held constant, measures the converter output. The potentiometer and converter are then switched to their initial positions, the current or voltage is reversed, and the two-step test is repeated. For increased reliability, it may be advisable to take an average of four determinations---two for each direction of current.

NOTE: If the transfer switch is left in the No. 2 (D-C) position, the thermoelement will remain energized while the preliminary settings are made for the next test point.

The corrected potentiometer setting in the V_s position of S_2 divided by the corrected shunt resistance or multiplied by the corrected volt box ratio is the "true" input current or voltage, Q_t. The current or voltage indicated by the converter, Q_i, is the corrected average of the potentiometer readings in the V_t position of S_2 multiplied by the factor given on the range switch. The percentage d-c correction for the converter is then simply $c = 100\ (Q_t - Q_i)/Q_n$ where Q_n is the nominal voltage or current.

Example:

Range	5 amps
Current (nominal)	5 amps
Shunt, R	0.09999 ohm
Potentiometer setting, V_s	0.50000 volt
Average potentiometer reading, V_t	0.49996 volt
Measured current $= V_s/R = I_m$	5.0005 amps
Indicated current $= V_t \times F = I_i$	4.9996 amps (F=10 for this range)
Converter correction $= I_m - I_i$	+0.0009 amp
Percent correction, c	+0.09/5 or +0.02%

NOTE: Potentiometer correction assumed negligible in the above example.

For an alternative method of making this calculation, see Appendix II.

When the volt-ampere converter is used to measure an a-c quantity, the true alternating voltage or current is $Q = V_tF\ (1 + 0.01c + 0.01d)$ where F is the factor marked on the range switch, c is the d-c correction

in percent for the range used and d is the percent ac-dc difference of the converter at the applied frequency.

Acceptable accuracy in this d-c test can be obtained only if the corrections to the standard cell, shunt box, volt box, and potentiometer are known to within ±0.01 percent or better at the working current or voltages and the corrections applied.

3. Calibration Procedure for Converters Having Double-Coil Indicators

For volt-ampere converters having the double-coil milliammeter as an error indicator the circuits and procedure are necessarily somewhat different. As before, two observers are required----one to operate the converter and one to measure the input with a potentiometer and volt box or shunt. A reversing switch for the test voltage and current should be provided, but the switch S_2 in figures 3 and 4 is not used.

A procedure paralleling the one described earlier can be used, but for best precision the following one is recommended.

With the decade multiplier or shunt dials set to the nominal test value, the transfer switch (SW in fig. 2) should be turned to position B (equivalent to No. 2 or D-C previously) and the No. 2 supply controls are adjusted to give a zero indication on the error indicator. The No. 1 supply controls are then adjusted until this internal d-c source balances the thermocouple output as indicated by a null on the galvanometer. The transfer switch is then turned to position A and the input voltage or current is adjusted by the observer at the converter until the galvanometer is again balanced. The input is held constant while the second observer measures the input voltage or current with the potentiometer and

volt box or shunt. The difference between the corrected potentiometer reading and the converter indication (dial settings) is then the correction to be applied to the converter with due attention to sign. Again the average of four readings----two for each direction of current----is advised.

Example:

Converter setting	150.0 volts
Error indicator	0.00
Converter indication, V_i	150.00 volts
Volt Box ratio, N	100 x 1.0002
Average potentiometer readings, V_s	1.49928 volts
Measured voltage = V_s N = V_m	149.958 volts
Converter Correction = V_m - V_i	-0.042 volts
Percent correction, c	-4.2/150 =-0.03%

4. Thermoelements

Ordinarily replacement thermoelements can be obtained from the manufacturer with guaranteed ac-dc differences of not more than 0.01 percent. Thus the ac-dc differences of a volt-ampere converter having a rated accuracy of 0.05 percent do not need to be redetermined when a thermoelement is replaced. The d-c calibration may be affected slightly if the new thermoelement has a reversed d-c difference, or (for instrument without compensating resistors) if its heater resistance is not at the nominal value. A d-c measurement on one or two ranges will show the magnitude of the effects.

5. A Voltage Comparator

A voltage comparator (figs. 5, 6, and 7) has been constructed at NBS which can be used instead of the external potentiometer for converter calibration. With it, a direct measurement of the percentage difference between V_s and V_t is made. The instrument has five ranges, .25, .5, .75, 1.0, and 1.5 volts, corresponding to the volt-ampere converter outputs obtained in the usual test. If the comparator input voltages (V_s and V_t) are nominally equal to any one of these range values, then the comparator indicates percent correction directly with the proper sign. If tests at other output levels are required, the comparator indication can be easily corrected as explained below.

Unlike the requirement of the potentiometer method, the shunt and volt box ranges must be selected so that V_s and V_t are nominally equal. This requirement is rarely difficult, although a wide-range shunt box may be needed.

Very fine controls for voltage and current are not required although good short-time stability is necessary. Again it is necessary to reverse the test current or voltage and take the average of values obtained for the two directions. The switches S_{1b} and S_2 shown in figures 3 and 4 are built into the voltage comparator and shown as S_v in figures 5 and 6. The shunt or volt box output and the volt-ampere converter output are connected directly to the V_s and V_t terminals, respectively.

Referring to figure 5, with the test voltage or current set within a few percent of the nominal value, the switch S_v is turned to V_s+ or V_s- depending on the polarity of V_s, and this input is balanced against the

internal Lindeck potentiometer by adjusting I_s until I_sR_s is equal to V_s. An internal galvanometer indicates equality. The I_s adjustment and the No. 1 (AC) balance on the VA converter being calibrated should be made simultaneously.

The No. 2 (DC) balance is then made on the converter, the switch S_v is moved to V_t and the converter output is compared with I_sR_s. If V_s and V_t are equal (a very special case) the galvanometer will again balance indicating that the volt box (or shunt) and the converter have equal corrections. If they are not equal, the balance can be restored by inserting the difference potential across the resistor R_c by adjusting I_c. A milliammeter in this circuit measures I_c and is marked so as to indicate the percent difference between V_s and V_t if the I_s meter is at full scale. When this indication is corrected for any shunt or volt box error, the converter correction is determined.

If V_t is smaller than V_s the switch S_c is reversed. This position of the switch is marked plus to show that the difference is to be added to the indication of the converter.

The correction formula for voltage ranges is shown in Appendix I to be $c = v + \frac{D_c}{D_s}$ where c is the percent correction of the volt-ampere converter, v is the percent volt box correction, D_c is the indication of the "correction" milliammeter (I_c) with its proper sign, and D_s is the indication of the one milliampere (full scale) instrument in the Lindeck potentiometer (I_s). It is expected that the comparator will nearly always be used with this instrument at full scale so that D_s is 1 and the formula is $c = v + D_c$. This is also the case for the current ranges. The formula,

derived in Appendix I, is $c = -u + \frac{D_c}{D_s}$ where u is the percent shunt correction and D_s is again one at full scale or rated input.

The NBS voltage comparator is built entirely of commercial parts. The rotary switches S_v and S_p have solid silver contacts and 10-turn, helically wound, 1000 ohm control resistors are used. All other resistors are in the 1/2 percent accuracy class and wire wound. The I_s circuit is supplied by two No. 6 dry cells and the I_c circuit by one. It is important that the current in the I_s circuit be stable to at least 0.01 percent for as long as it takes to make the second balance. The meters are of the panel type in the two percent accuracy class.

It should be noted here that high accuracy in comparator circuits is not necessary. The "correction" meter has a full scale range of 0.1 percent so that a ten percent error is necessary in its associated resistors to cause a 0.01 percent error in the resulting volt-ampere converter correction. Furthermore, as suggested earlier, exact setting of the test voltage or current is not necessary. It can be shown that if the volt-ampere converter input differs from the nominal value by nine percent, the indicated converter correction (c) will not be in error by more than 0.01 percent even if the converter correction is as large as 0.1 percent. Therefore, the D_s term in the equations above may be considered to be unity if it is within a few percent of full scale.

The voltage comparator has the advantage of being low in cost and easily constructed and used. It frees a precision potentiometer for other work, makes very fine control unnecessary and greatly simplifies the calculations.

The author acknowledges the assistance of Mr. F. L. Hermach who offered many valuable suggestions and who originally developed the equations given in Appendix II.

6. References

[1] F. L. Hermach and E. S. Williams, Multirange Audiofrequency Thermocouple Instruments of High Accuracy, J. Research, 52, 227, (1954) RP2494.

[2] F. L. Hermach and E. S. Williams, A Wide-Range Volt-Ampere Converter for Current and Voltage Measurements, AIEE Transactions (Communications and Electronics), 384, (September 1959).

Appendix I

Derivation of Equations for the Voltage Comparator

The voltage to be measured (V_p) by the volt-ampere converter (with a potentiometer connected to the output) is $V_p = V_t F (1 + c)$ where V_t is the converter output, F is the multiplying factor, and c is the proportional correction to F. The same voltage (V_p) as measured by the volt box and potentiometer is $V_p = V_s N (1 + v)$ where V_s is the potentiometer reading, N is the volt box ratio, and v is the proportional correction to N. Therefore,

$$V_t F (1 + c) = V_s N (1 + v). \qquad (1)$$

When the two balances are made on the voltage comparator $V_s = I_s R_s$ and $V_t = I_s R_s - I_c R_c$ for the "plus" position of switch S_c so that

$$\frac{N(1 + v)}{F(1 + c)} = 1 - \frac{I_c R_c}{I_s R_s}.$$

In order that V_s and V_t be nominally equal, the volt box range must be chosen so that F = N. The one milliampere instrument in the I_s circuit is read directly so that $D_s = I_s$ where its indication is designated as D_s. The 0.5 milliampere instrument in the I_c circuit is marked to indicate 0.1 at full scale so that $I_c = 5 D_c$ where D_c is the indication of the "correction" meter. Then with the resistors chosen so that $R_c/R_s = 1/500$, we may write

$$\frac{1 + v}{1 + c} = 1 - \frac{5 D_c}{500 D_s}.$$

If v and c are very much less than unity then, very closely, $c = v + D_c/100D_s$ and if c and v are in percent this becomes

$$c = v + \frac{D_c}{D_s}. \qquad (2)$$

Similarly, a current measured by the volt-ampere converter is $I_p = V_t F (1 + c)$ where I_p is the measured current and the other terms are

the same as above. The same current measured with the shunt and potentiometer is $I_p = V_s/R\ (1 + u)$ where R is the nominal resistance of the shunt, u is the shunt correction and V_s is the potentiometer reading, therefore,

$$\frac{V_s}{R\ (1 + u)} = V_t F\ (1 + c). \qquad (3)$$

When the two balances are made on the voltage comparator

$$V_s = I_s R_s \text{ and } V_t = I_s R_s - I_c R_c$$

so that

$$\frac{1}{F\ (1 + c)\ R\ (1 + u)} = 1 - \frac{I_c R_c}{I_s R_s}.$$

In order that V_s and V_t be nominally equal, the shunt must be chosen so that FR = 1.

Therefore, with $R_c/R_s = 1/500$, $c = -u + I_c/500\ I_s$ and proceeding as above, we have

$$c = -u + \frac{D_c}{D_s} \qquad (4)$$

neglecting second and higher order terms.

Appendix II

Derivation of Equations for the Potentiometer Method

The calculations illustrated earlier for converters used with a potentiometer can be shortened considerably by using formulas similar to those above. The equations (1) and (3) are valid whether a potentiometer or voltage comparator is used.

Considering equations (1) for voltage measurements, we may rewrite it

$$\frac{V_s N}{V_t F} = \frac{1 + c}{1 + v}.$$

The nominal values of V_s and V_t are not necessarily equal but in any case the ratio $V_s N/V_t F$ is nominally 1. If V_s is set exactly to its

nominal value, and if we substitute for V_t a value V_{tn} (1 + a), where V_{tn} is the nominal value, and a is a fractional correction to the nominal value, i.e., $a = (V_t - V_{tn})/V_{tn}$, then $V_s N/V_{tn} F = 1$ and

$$\frac{V_s N}{F\, V_{tn}(1 + a)} = \frac{1 + c}{1 + v}$$

for which

$$c = v - a \tag{5}$$

neglecting second and higher order terms.

Similarly, we may write equation (3)

$$\frac{V_s}{RFV_t} = (1 + u)\ (1 + c).$$

In this case the ratio V_s/RFV_t is nominally 1. If V_s is set exactly to its nominal value and $V_t = V_{tn}(1 + a)$ as before, we then have

$$\frac{V_s}{RFV_{tn}(1 + a)} = (1 + u)(1 + c)$$

from which

$$c = -a - u. \tag{6}$$

neglecting second and higher order terms.

Example:

Range	5 amps
Current	5 amps
Shunt R	0.09999 ohms (u = -0.010%)
Potentiometer setting V_s	0.50000 volts
Average potentiometer reading V_t	0.49996 volts (a = -0.008%)
Converter d-c correction c = -a -u	+ 0.02%

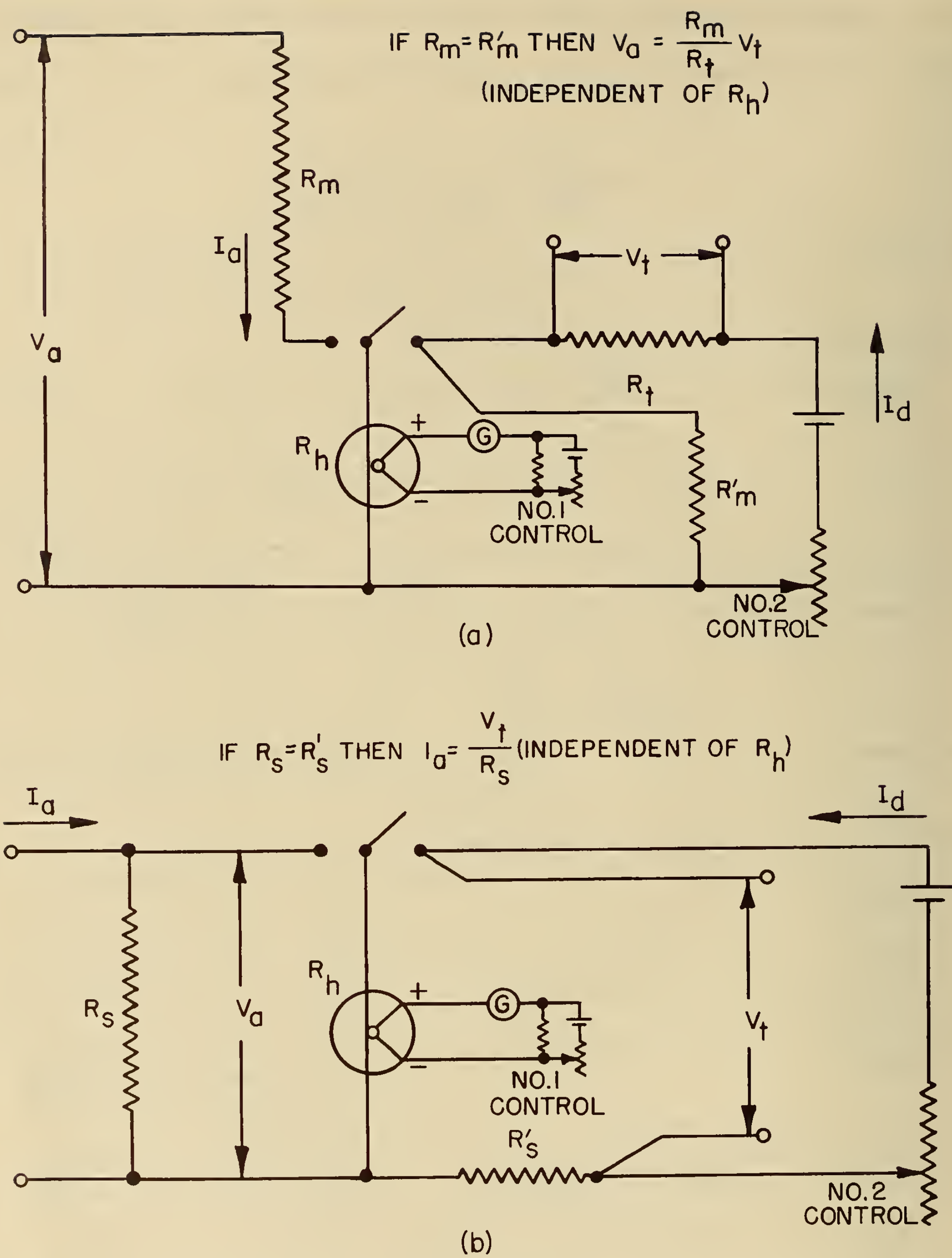

Figure 1. Simplified diagram of volt-ampere converter; (a) For voltage measurements; (b) For current measurements

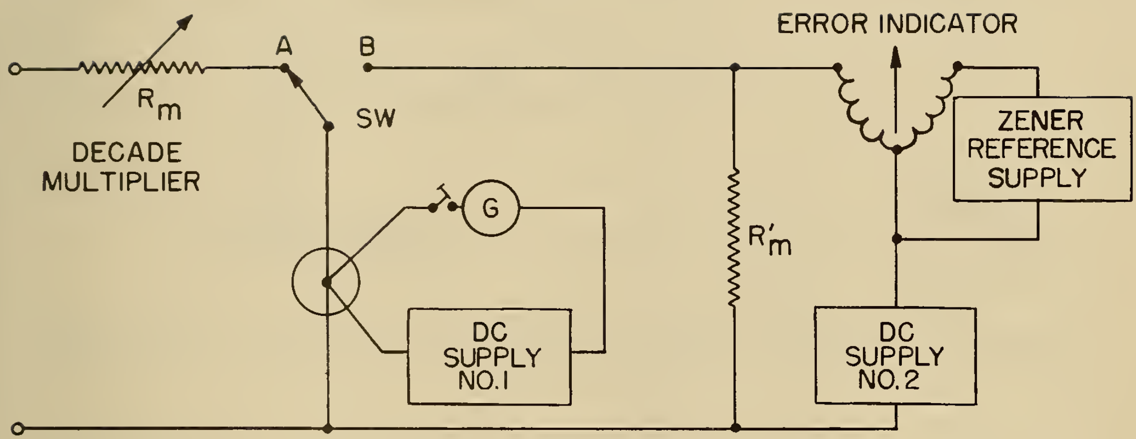

Figure 2. Simplified diagram of volt-ampere converter with error indicator (for voltage measurements)

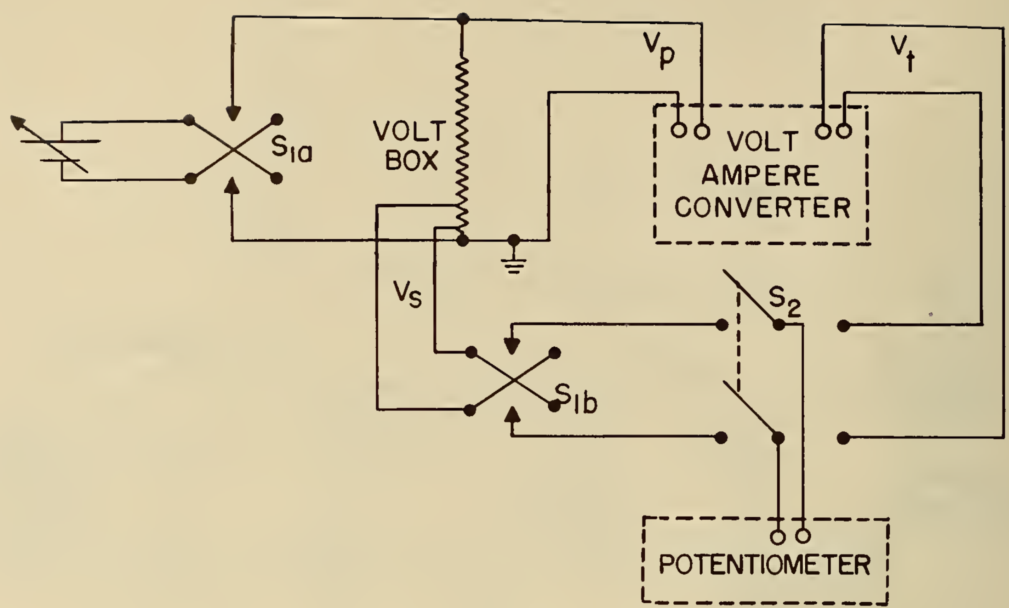

Figure 3. Calibration circuit for volt-ampere converter voltage ranges

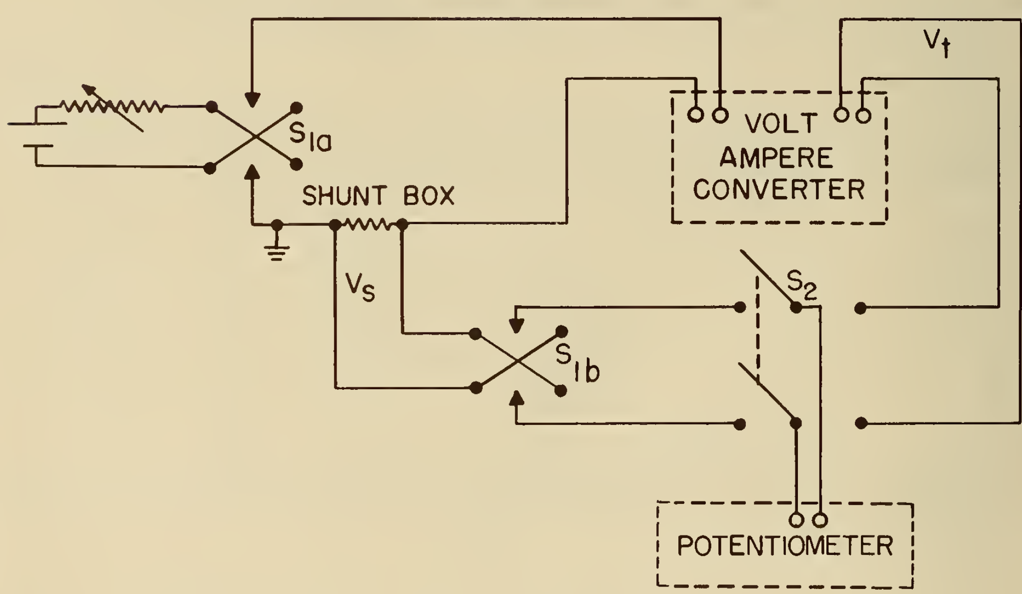

Figure 4. Calibration circuit for volt-ampere converter current ranges

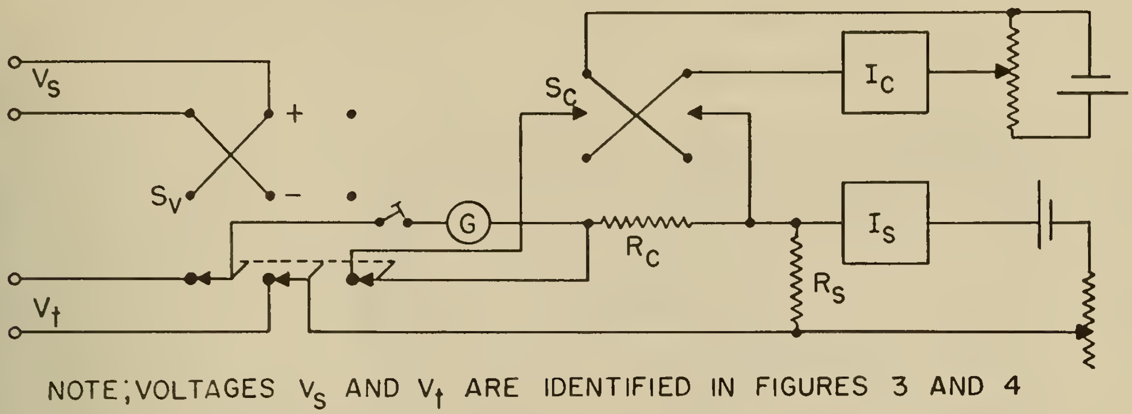

Figure 5. Simplified diagram of voltage comparator

NOTE: Voltages V_s and V_t are identified in figures 3 and 4

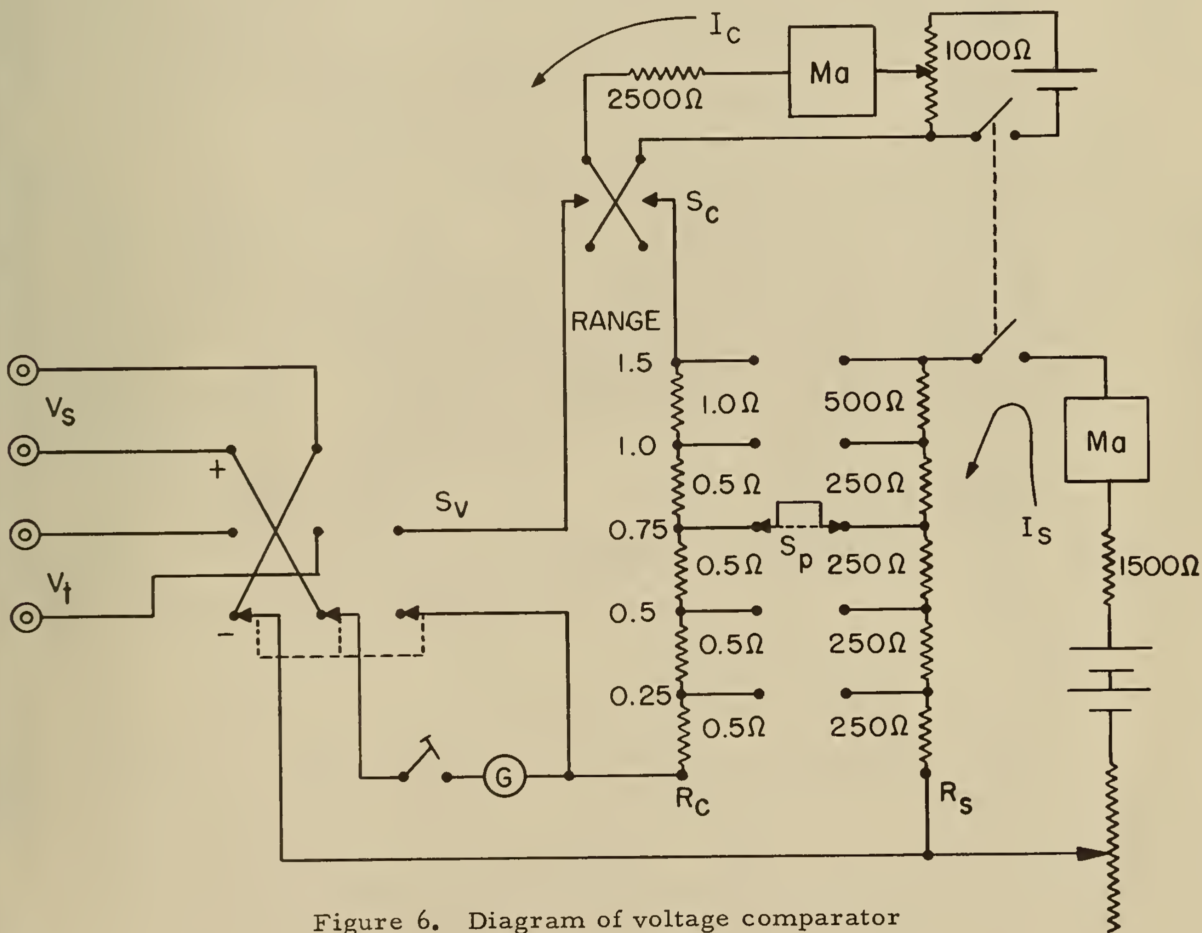

Figure 6. Diagram of voltage comparator

Figure 7. Photograph of voltage comparator

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Mechanics. Sound. Pressure and Vacuum. Fluid Mechanics. Engineering Mechanics. Rheology. Combustion Controls.

Polymers. Macromolecules: Synthesis and Structure. Polymer Chemistry. Polymer Physics. Polymer Characterization. Polymer Evaluation and Testing. Applied Polymer Standards and Research. Dental Research.

Metallurgy. Engineering Metallurgy. Microscopy and Diffraction. Metal Reactions. Metal Physics. Electrolysis and Metal Deposition.

Inorganic Solids. Engineering Ceramics. Glass. Solid State Chemistry. Crystal Growth. Physical Properties. Crystallography.

Building Research. Structural Engineering. Fire Research. Mechanical Systems. Organic Building Materials. Codes and Safety Standards. Heat Transfer. Inorganic Building Materials. Metallic Building Materials.

Applied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics. Operations Research.

Data Processing Systems. Components and Techniques. Computer Technology. Measurements Automation. Engineering Applications. Systems Analysis.

Atomic Physics. Spectroscopy. Infrared Spectroscopy. Far Ultraviolet Physics. Solid State Physics. Electron Physics. Atomic Physics. Plasma Spectroscopy.

Instrumentation. Engineering Electronics. Electron Devices. Electronic Instrumentation. Mechanical Instruments. Basic Instrumentation.

Physical Chemistry. Thermochemistry. Surface Chemistry. Organic Chemistry. Molecular Spectroscopy. Elementary Processes. Mass Spectrometry. Photochemistry and Radiation Chemistry.

Office of Weights and Measures.

BOULDER, COLO.

Cryogenic Engineering Laboratory. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Cryogenic Technical Services.

CENTRAL RADIO PROPAGATION LABORATORY

Ionosphere Research and Propagation. Low Frequency and Very Low Frequency Research. Ionosphere Research. Prediction Services. Sun-Earth Relationships. Field Engineering. Radio Warning Services. Vertical Soundings Research.

Radio Propagation Engineering. Data Reduction Instrumentation. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Propagation-Terrain Effects. Radio-Meteorology. Lower Atmosphere Physics.

Radio Systems. Applied Electromagnetic Theory. High Frequency and Very High Frequency Research. Frequency Utilization. Modulation Research. Antenna Research. Radiodetermination.

Upper Atmosphere and Space Physics. Upper Atmosphere and Plasma Physics. High Latitude Ionosphere Physics. Ionosphere and Exosphere Scatter. Airglow and Aurora. Ionospheric Radio Astronomy.

RADIO STANDARDS LABORATORY

Radio Physics. Radio Broadcast Service. Radio and Microwave Materials. Atomic Frequency and Time-Interval Standards. Radio Plasma. Millimeter-Wave Research.

Circuit Standards. High Frequency Electrical Standards. High Frequency Calibration Services. High Frequency Impedance Standards. Microwave Calibration Services. Microwave Circuit Standards. Low Frequency Calibration Services.

NBS